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THE FUSION TORCH

CLOSING THE CYCLE FROM USE TO REUSE

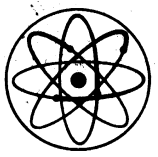
by

Bernard J. Eastlund

and

William C. Gough

May 15, 1969



Division of Research

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ACKNOWLEDGEMENT

The concepts expressed in this paper evolved from the strong belief on the part of the authors that controlled fusion should not be viewed solely as another means of providing heat to generate electricity via the conventional steam turbine cycle. Rather controlled fusion should be investigated as a new *prime energy source* with potential inherent advantages uniquely suited for direct conversion of energy into forms useful for society. We believe the fusion torch concept to be one such important advantage obtainable from fusion energy.

For this concept to reach its present stage required the contributions of many persons. We would like to take this opportunity to acknowledge these contributions.

First, we would like to thank the U.S. Atomic Energy Commission for fostering an atmosphere where independent thought could thrive. In particular, one author would like to thank Dr. Arthur E. Ruark, Senior Associate Director, Division of Research, and Dr. Paul W. McDaniel, Director, Division of Research for supporting his participation in a year of AEC–sponsored study at Harvard University on the interaction of science upon our society. This year provided the foundation for many of the broader thoughts expressed in the paper.

Second, we would like to thank Dr. Amasa S. Bishop, Assistant Director for Controlled Thermonuclear Research who gives his staff the freedom to explore ideas off the main stream, and then, despite the skepticism of others, provided the inspiration and encouragement to carry through the development of ideas.

Third, we want to acknowledge the many people, too numerous to mention, throughout industry, government, the national laboratories and universities who freely provided comments, information, and advise as our ideas progressed. These inputs served as the building blocks for the evolution of our thoughts on subjects as wide-ranging as those discussed in this paper. We found the criticisms of our initial thoughts to be extremely helpful, often resulting in the development of new ideas.

Last, but not least, we wish to praise the patience and assistance of our wives, Sherrie and Marion, who cheerfully accepted the fact that much work had to be done at nights and weekends.

SYNOPSIS OF THE FUSION TORCH CONCEPT

Bernard J. Eastlund and William C. Gough

Two concepts for the application of the ultra-high temperature plasmas now available in fusion experiments and eventually in controlled fusion reactors will be discussed. The first concept is the use of ultra-high temperature plasma, in the form of a fusion torch, to reduce *any* material to its basic elements for separation. The second concept is the use of the fusion torch to transform the energy in the ultra-high temperature plasma into a radiation field, to permit process heating to be done *in the body* of a fluid.

The basic concept of the fusion torch assumes that a plasma is transferred from the region where it is generated through a connecting region which isolates it from the plasma source to an interaction region. In the interaction region the pure ultra-high temperature plasma is ready for fusion torch applications.

The first application is the use of the fusion torch to reduce materials to their basic elements. For control of operations, plasma temperature and flow velocity in the interaction region can be regulated by expansion and contraction of the confining magnetic field. The ability to do this can be shown from the plasma's energy conservation equation. The high thermal conductivity and large energy flux of the fusion torch plasma leads to shock vaporization and ionization of a solid rather than ablative cooling (as occurs in a low temperature arc plasma). The result is that plasma energy is transferred to the solid on a time scale characteristic of the residence time of the solid in the fusion torch and without excessive impurity radiation losses. Analysis of laser produced plasma supports this contention although an experimental verification is needed. The status of plasma technology permits such an experiment to be carried out now.

The plasma, composed of ionic species of the solid, proceeds into a separation region where a variety of techniques can be used to segregate the ionic species according to either atomic number or atomic mass. Possible separation techniques include (a) electromagnetic, (b) quenching the plasma flow stream, (c) selective recombination, or (d) charge exchange. Using *energy consuming* ultra-high temperature plasmas, limited applications may be practical now for ore reduction or certain scrap recovery. When fusion reactors are available, volume of materials equal to thousands of tons per day could be handled in a single plant. The handling of urban wastes then becomes a possibility. Thus the ultimate goal of closing the material's cycle from use to reuse could be achieved.

The second application of the fusion torch is to transform ultra-high temperature plasma energy into a radiation field by injecting trace amounts of selected materials into the torch. The emission frequency and intensity of the emitted radiation can be controlled by varying the amount and type of material injected into the plasma. It is possible to maximize the energy in chosen narrow spectral bands. This can be shown from the time dependent coronal equilibrium model which is valid for fusion plasma conditions (this would not be the case for a plasma arc).

The radiation can be generated in the ultraviolet (or another range if desired), transmitted through a window material, and absorbed in a bulk working fluid. The present limitation on bulk processing established by surface heat transfer has been removed. For fusion reactors, the intermediate step of conversion from a prime energy source to electricity has likewise been eliminated.

A flux of ultraviolet energy as high as megawatts per square meter could be obtained if desired. The absorption coefficient for ultraviolet radiation in the window has been demonstrated to be very low for special synthetic quartz. Based upon recent work on radiation resistant window material, suitable window material could be developed even for the highest fluxes. The window material need not be in physical contact with the fluid since the fusion torch could be used much like a heat lamp to illuminate a large area of material.

The absorption depth of ultraviolet radiation in water is about one meter, thus permitting bulk heating. The ultraviolet energy could be applied to any of the current uses of such energy, for example sterilization and photolysis. With the availability of fusion power, large volume applications such as desalination of water, processing of urban sewage, plasma chemistry and the conversion to electricity through fuel cells become possible.

There is an immediacy to the problems capable of solution by the fusion torch and hence by fusion power which warrants serious attention to the concept. The world is now on the steep slope of a rapidly rising transient driven by a population explosion. Over the next 30 years, there appears little probability that the world population can be significantly reduced below the projected seven billion persons for the year 2000. The result will be extraordinary demands for food and raw material accompanied by growing volumes of wastes and pollutants.

Unprecedented amounts of auxiliary energy will be required to amplify the amount of the sun's energy that can be harnessed by civilization. This amplification is essential if large urban populations are to live in an industrialized society and a habitable environment. The choice of energy sources will be limited. Usable for a short term are fossil fuels and fission water reactors, for the longer terms we must depend upon three potential sources of energy: (1) conversion of the sun's energy, (2) fission breeder reactors, or (3) controlled fusion energy. All other energy sources such as water power are insignificant for meeting the world's future energy requirements. Each major energy source has unresolved questions that may limit its availability or make the choice of an alternate desirable. Such questions as the effect of CO_2 buildup and other pollutants upon the atmosphere, the limitations enforced by thermal effects, the safety of the system, the buildup and storage of radioactive wastes in the environment, the proliferation of nuclear materials, and the economic, technological and scientific feasibility of the energy sources could make the *option* of an alternate energy source crucial to the preservation of an industrialized civilization.

Research aimed at controlling fusion energy has been making significant advances. Fusion power offers many advantages as an energy source. Its fuel is inexpensive, widely available, and virtually inexhaustible. It is inherently safe against nuclear explosion. It releases no combustion products to the air and its reaction products are non-radioactive. It has the potential of operating at very high efficiencies and thereby greatly reducing thermal pollution.

Over 5 years ago, controlled fusion research achieved its first goal of heating a dilute gas of fusion fuel to temperatures of hundreds of millions of degrees. Such ultra-high temperature plasmas are now routinely produced. These plasmas could be applied to present day industrial needs. By taking full advantage of the unique properties of fusion plasmas that will be available from future controlled thermonuclear energy sources, solution to pressing problems in the United States will be possible.

Three areas are becoming of serious concern in the United States–the disposal of solid wastes, the availability of fresh water, and adequate supplies of raw materials. Over the 35 year period from 1965-2000, almost 10 billion tons of solid refuse will have been accumulated in the United States. If compacted and buried to a depth of 20 feet, a land area the size of the State of Rhode Island would be required. Water shortages exist now in certain parts of the United States and are projected to grow worse. Ground-water supplies are already overdrawn in the Southwest. Large water desalting plants have been proposed as a possible solution. The United States is today a have-not nation where raw materials are concerned. Of the 100 minerals most important to its industries, the United States possesses within its national boundaries adequate supplies of only about a dozen.

The fusion torch concept offers the ability to meet the urgent future needs for raw materials including water and to eliminate the buildup of wastes. Thus, the fusion torch concept offers the potential for the immediate application of ultra-high temperature plasma and can add impetus for the development of fusion power.

TABLE OF CONTENTS

THE FUSION TORCH – CLOSING THE CYCLE FROM USE TO REUSE

Introduction 1

Status of Controlled Fusion 1

I. General Problems of an Industrialized Society 3

A. Energy Requirements and Civilization 3

1. Importance of Energy 4
2. Energy Availability 4
3. Energy Needs and Population Expansion 4

B. Waste Products 6

C. Raw Material Supply 7

D. Thermal Effects 8

II. Technical Aspects of the Fusion Torch 9

A. Conservation Equations 9

1. Conservation of Mass 9
2. Conservation of Momentum 9
3. Conservation of Energy 9

B. Connection Region 10

C. Control of Plasma Flow Parameters 10

D. Plasma-Gas Interaction 10

E. Plasma-Solid Interaction 11

III. Waste Products Elimination – Raw Material Recovery 12

A. Separation Techniques 12

1. Electromagnetic Separation 12
2. Quench Techniques 13
3. Selective Recombination 13
4. Charge Exchange 13
5. General Comments 13

IV. Transfer of Plasma Kinetic Energy to a Radiation Field 14

1. Ultraviolet Energy Transfer to Water 14
2. Applications (Desalination, Sewage Treatment, etc.) 15

V. Plasma Chemistry 16

VI. Conclusions 17

Appendix I Energy Transport to a Spherical Solid Immersed in a Magnetoplasma 19

References 20

INTRODUCTION

By the year 2000, the population of the United States will have grown to an estimated 315 million. With a population of this magnitude, a highly industrialized society such as ours will demand large amounts of energy and will generate large amounts of wastes while it consumes its finite supplies of raw materials. We suggest that thermonuclear fusion reactors could essentially solve the urban problems of energy, waste disposal and raw materials supply.

We propose a number of concepts. First, that the energy of a fusion plasma be used as an ultra-high temperature torch (fusion torch)[1] to close the basic link from user back to resource. This would be accomplished by vaporizing and ionizing solids (for example, ores or waste products) in the plasma and then separating the elements from the mixture of ionized species. A fusion plasma is able to vaporize solids easily by the propagation of shock waves. This is because of the plasma's tremendously large flux of random kinetic energy and its high thermal conductivity. (Conventional plasma arcs cannot supply this much energy. Arc work is noted in the literature.[2,3,4,5])

Second, we show that the plasma can be used to radiantly heat bulk fluids and thus permit entirely new approaches to such important goals as desalination. This is accomplished by producing intense ultraviolet radiation from high Z material injected in the plasma. The transparency of the plasma to these wavelengths and its "coronal" properites lead to this possibility.

Other applications of the fusion torch, such as its use in plasma chemistry are also treated. In brief, we indicate a tremendouse range of fusion plasma applications. These applications are made possible because of the unique properties of such an environment.

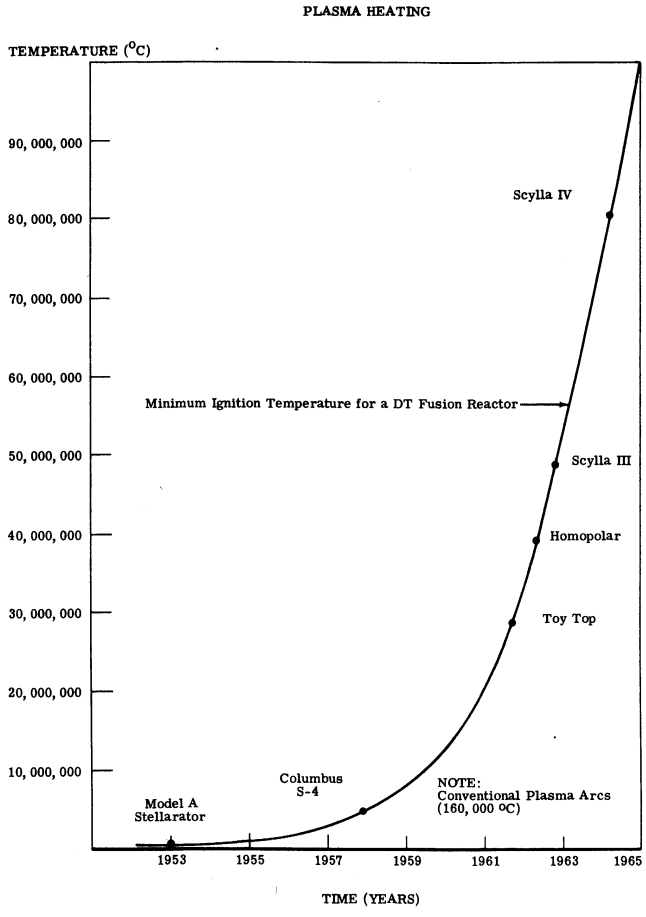


Figure 1

Some of the long range factors influencing the growth of a technological society will be described in section I. The discussion is important and shows the problems are enormous and the number of possible solutions to be rather limited. However, energy consuming fusion plasmas (as opposed to energy producing reactors) exist at the present time and short range applications could be developed.

The technical aspects of the fusion torch concept will be described in section II. Its use for waste product elimination and raw material recovery will be discussed in section III. Section IV describes possible uses of ultraviolet radiation from such a plasma. Other uses, including plasma chemistry are described in section V.

Before proceeding however, a few remarks on the status of controlled fusion power are in order.

Status of Controlled Fusion:

The achievement of useful controlled fusion energy requires that we (a) heat a dilute gas of fusion fuel to temperatures of hundreds of millions of degrees, and (b) contain it long enough (and at sufficient purity) for an appreciable fraction of the fuel to react. The first goal was to obtain plasmas above the ideal ignition temperature, i.e. the lowest possible operating temperatures for a self-sustaining fusion reactor. Figure 1 shows that this goal has been achieved. Such plasmas, at the densities needed for controlled fusion, are now routinely produced. Note the location of conventional arcs on this plot.

The world effort then converged upon the problem of how to adequately confine the hot plasmas. Progress has been accelerating as the result of increased correlation between theory and experiment. Also, the use of advanced computers for plasma simulation has opened up a new area to complement theory and experiment, particularly in non-linear regimes. The following three figures[6] give quantitative examples of improvements in plasma confinement that represent part of the foundation for current optimism in the quest for fusion power. Figure 2 shows the improved confinement in toroidal systems that is now being obtained. Figure 3 shows the excellent confinement measured in a high density plasma experiment. As seen, the experimental points agree closely with the slow *classical* rate of cross-field loss, and is clearly at variance with the more rapid "Bohm" loss rate. Figure 4 shows the improvements with time that have been obtained in the 2X mirror machine that operates at temperatures of 50 million degrees. Recently, the Soviets reported a major achievement in their Tokamak experiments where a 5,000,000°C plasma with a

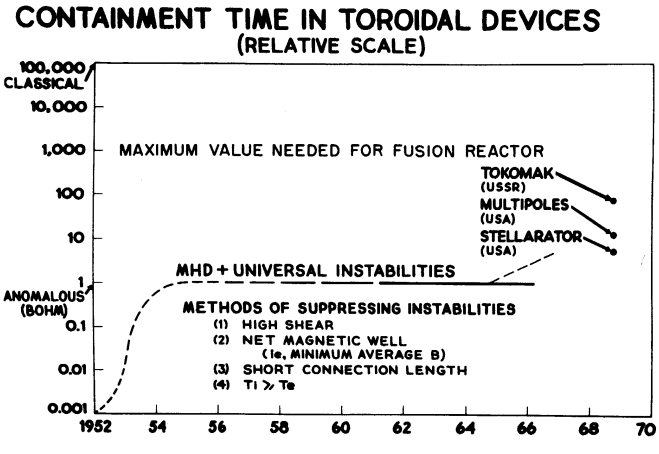


Figure 2

density of 5 x 10^{13} electrons per cubic centimeter has been contained for 1/50 of a second.[7] This is equivalent to about 100 Bohm times which our technology studies show is close to the minimum confinement conditions needed for a fusion reactor.[8]

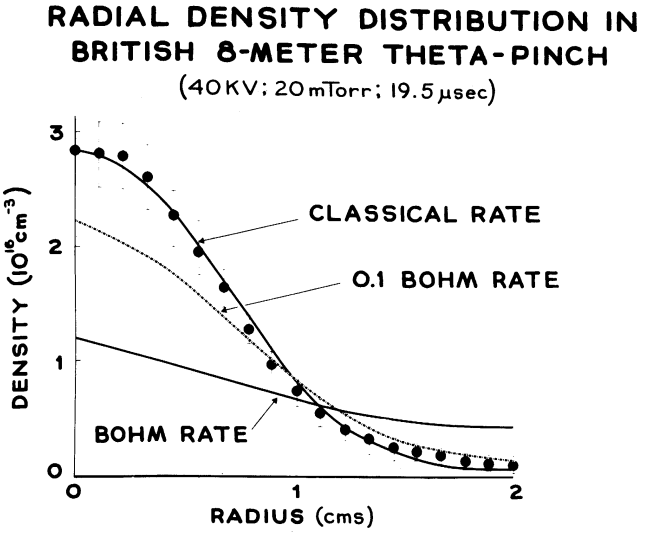


Figure 3

A new generation of fusion experiments is now being built in the U.S., U.S.S.R., and elsewhere to extend these results. Much hard work and many unknowns remain, but the scientific feasibility of fusion may well be demonstrated by this new generation of experiments.

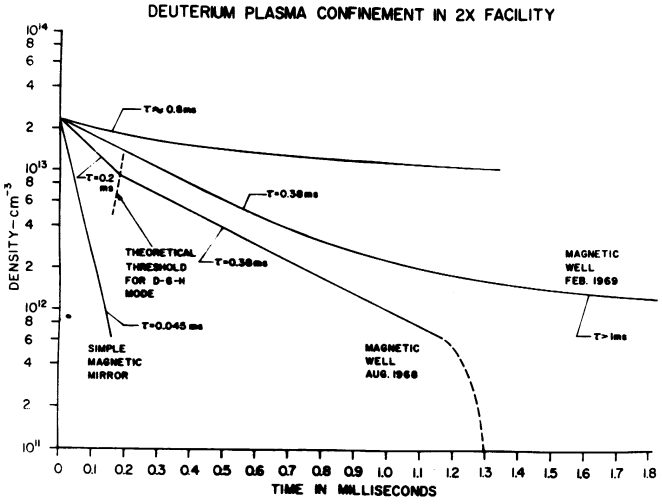


Figure 4

In this section, we shall present information on energy needs and availability, waste products, raw materials supplies, and thermal effects (i.e. misplaced energy). The importance of fusion power to these areas will be pointed out. Later sections will describe in more detail the proposed use of fusion plasmas to help alleviate the waste product and raw material problems.

Energy consumption in the United States is projected to grow as shown in Figure 5.[9] An increasing percent of this energy will be used in electricity. By the year 2020 the consumption of electricity is expected to be double that of the year 2000.[10] Part of the expanded energy consumption is due to an increased standard of living but a major factor is the growth of the U.S. population. Figure 6 shows that this population will be primarily in urban areas of 100,000 or more.[11,12] The energy sources of the future must meet the needs of densely packed urban centers—cheaply, safely and with minimum adverse effect upon the environment.

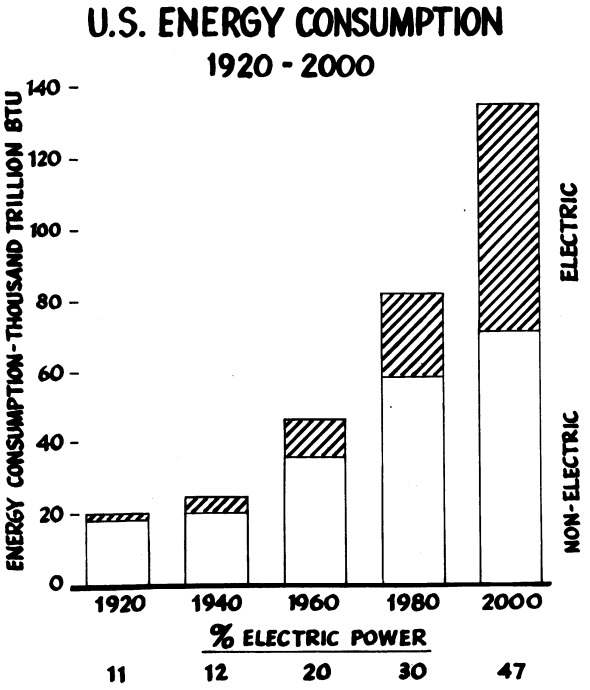


Figure 5

"Cost" comparisons for energy sources are usually based upon power costs at the bus-bar. On this basis alone, fusion power appears attractive. An important factor is that the fuel costs for fusion plants are negligible. Figure 7 lists the possible fusion fuel cycles. The world reserves of the raw materials for these cycles—deuterium (an isotope of hydrogen) and lithium are essentially unlimited.[13] Deuterium is present in all water as the molecule HDO.

However, a major portion of the cost of power occurs after leaving the bus-bar.[14] Reduced costs to the customer can be obtained by locating power plants close to load centers.[15,16] Fusion power plants will have this capability. They are inherently safe and are not subject to nuclear run-away or core meltdown accidents.[17] The only fusion fuel cycle that would use radioactive fuel would be D-T. Even in this case the radioactive inventory in the plant, should it be released due to an external source such as an earthquake[18,19] or military attack,[20] would be at least a million times less than an equivalent fission system.[16,21] The reason for this is that the reaction products from fusion are non-radioactive. The ash from a fusion reactor is helium, a valuable byproduct that will be in short supply by the year 2000.[22] Hence the transportation of fuel and ash and their storage will not be a problem.[15,23,24] Another important consideration is the fact

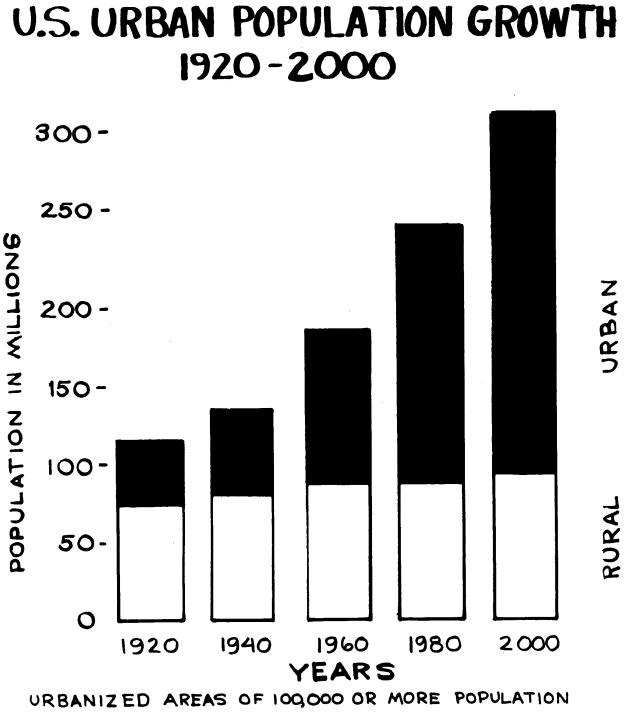


Figure 6

that the only material in fusion fuel cycles which could conceivably have weapons potential is tritium, although this requires a fission weapon as a trigger. Depending on the fuel cycle or combination of fuel cycles chosen, the possibility of diversion of tritium from a fusion reactor could be made either small or nonexistent.[25,26]

A. ENERGY REQUIREMENTS AND AVAILABILITY

To place the future potential of ultra-high temperature plasmas in perspective, the relation of controlled fusion energy to man's needs to obtain, control and manipulate the energy necessary for an advanced industrial civilization will be briefly discussed. Studies of the technological aspects of fusion power conclude that economic fusion reactors will most likely be large; about 2,000 to 10,000 MW(e). This is a size range which will be typical of the larger power plants in the future. For example, a recent government study projects that 147 thermal generating plants in the United States for the year 1990 will have capacities from 2,000 to 10,000 MW.[15]

POSSIBLE FUSION FUEL CYCLES

	NET CHARGED PARTICLES (MeV)	NEUTRONS (MeV)	TYPICAL RADIATION
$D + T \rightarrow He^4 + n$	3.37 (19%)	14.1 (80%)	0.13 (1%)
$D + D \rightarrow He^3 + m$	1.2 (33%)	1.2 (33%)	1.2 (33%)
$D + D \rightarrow T + H$			
$D + He^3 \rightarrow He^4 + H$	14.4 (79%)	0	3.9 (21%)

Figure 7

1. Importance of Energy

The importance of abundant energy to achieving a high standard of living is clearly illustrated in Figure 8.[13] Less well understood is the basic reason behind this relationship. The energy now being released from fossil fuels, water power, and nuclear reactors should be considered as *auxiliary* energy to the vast supplies of energy being delivered to earth from our sun. This auxiliary energy is then used in the feedback loop shown in Figure 9 to widen the gate and thus permit an amplification of the amount of the sun's energy that can be harnessed by civilization.[27] This is accomplished through the use of auxiliary energy to produce fertilizers, pesticides, improved seeds, farm machinery, etc. The result has been a large urban population supported by a small farm population, but all critically dependent upon abundant auxiliary energy supplies. The direct relationship between the amount of auxiliary energy being used and the agricultural output possible is shown in Figure 10.[27] Thus, world population, available food supplies, standard of living and abundant cheap energy are all very interdependent quantities. The significance of this fact to the problems of the future should not be overlooked.

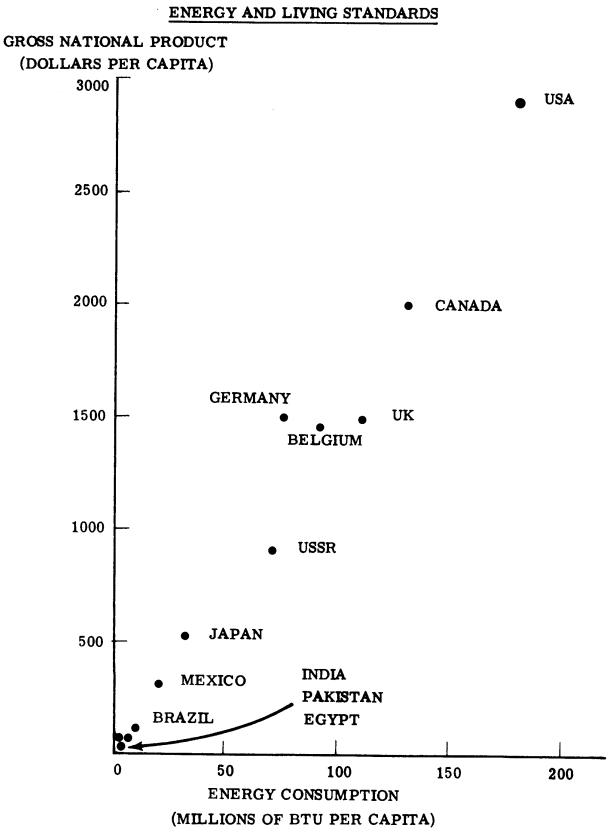


Figure 8

2. Energy Availability

The energy needs of the United States up to 2000-2020AD can be met by existing energy sources, i.e., by fossil fuels and fission light water reactors.[13,28,29,30] These energy needs can probably be met without major cost increases.[28,31] On a world wide basis the picture is less secure. *When widespread industrialization is assumed*, an analysis of fuel use versus time shows that the middle 80 percent of the world's supply of crude oil and natural gas would be consumed during a period of 15-20 years and that of coal in less than a century.[30] Until the current technological efficiency for recovering the heat content of fissionable materials is increased above its present value of 1-2 percent,

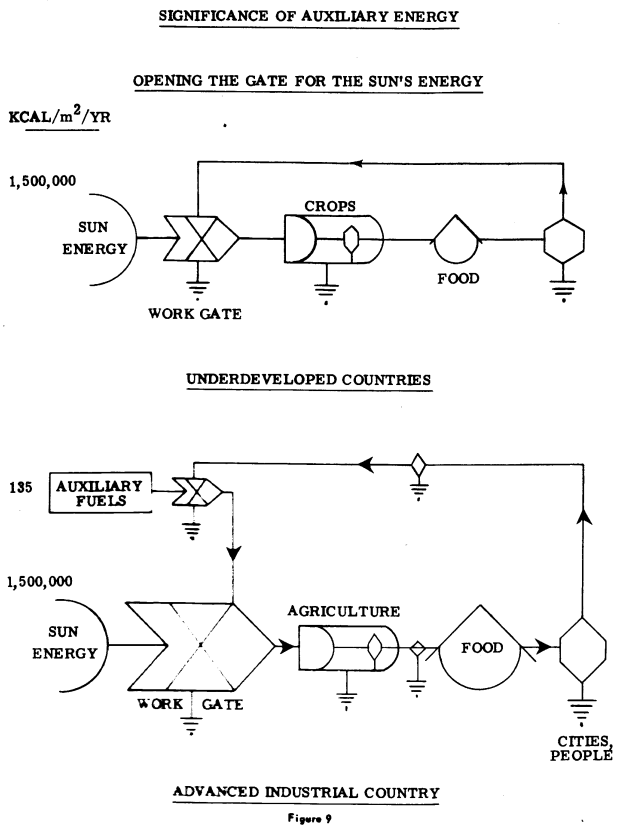


Figure 9

abundant reserves of fissionable material at or near current costs will not be available.[32,33] This situation is illustrated in Figure 11 on "Limited Energy Sources."[34]

The outlook for future energy resources becomes bright once one of the three potential sources available for the production of large amounts of energy can competitively produce power. The three major energy sources are: fission breeder reactors,[35] solar energy,[36,37] and controlled fusion reactors.[38,39] The "Infinite Energy Sources" are presented in Figure 12.[30] The "infinite" nature of fusion energy is apparent when we consider that in the ocean alone the reserves of deuterium are over 8 billion times and those of lithium 80 million times the world energy requirements in the year 2000.[13]

Although leadtimes are long and there are uncertainties about eventual success, mankind does have some latitude in choosing the timescale upon which large-scale energy sources will become available. We believe there are three criteria that should govern the choice of future energy sources. They are the ability to:

1. Minimize cost of delivered energy to the consumer.
2. Minimize undesirable ecological and biological effects.
3. Perform functions important to human needs more effectively than other energy sources.

Figures 11 and 12 show that there are unresolved questions associated with each major energy source that may limit its availability, or make the choice of an alternate desirable.[40,41] Since energy is essential to the preservation of an industrial civilization, the option of an alternate major energy source could prove crucial if serious unforseen ecological problems arise.

3. Energy Needs and Population Expansion

To obtain a perspective on the time scale upon which new major energy sources will be needed, the energy consumption pattern of mankind should be reviewed over a long period, as shown in Figure 13.[30] When placed upon such a scale, the recent rapid rise in energy consumption and population are seen to represent a transient that will

take mankind from one steady state condition to a new state. The final end state will depend upon human foresight as indicated by the assumptions.

The rapidly increasing world population is the driving force behind this transient. If the world population expansion is *not*

ENERGY AND FOOD

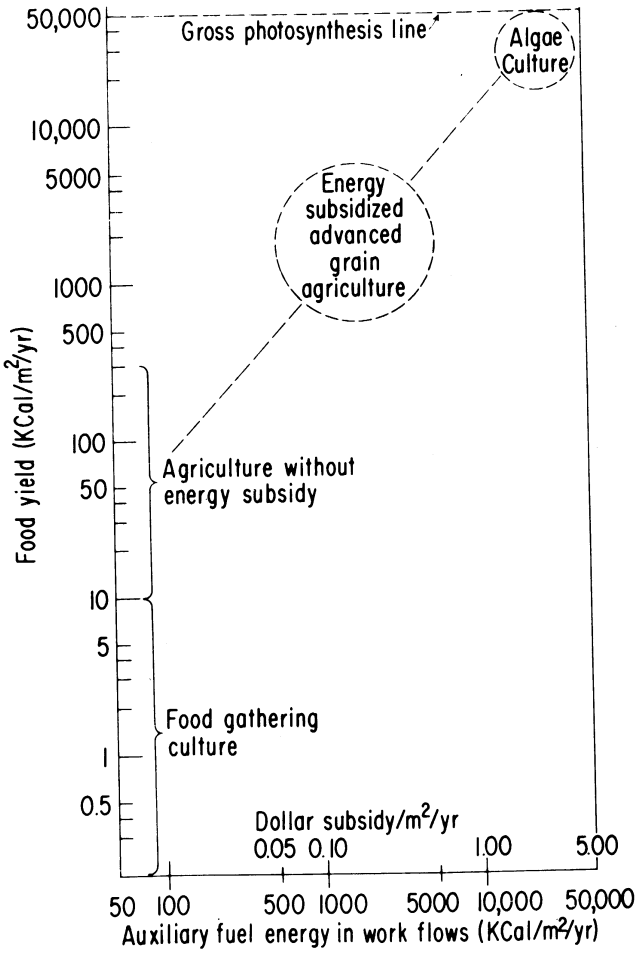


Figure 10

LIMITED ENERGY SOURCES

FOSSIL FUELS:
CONCERN: A LIMITED AND IRREPLACABLE NATURAL RESOURCE
QUESTION: ATMOSPHERE CO_2 BUILDUP - EFFECT ON WEATHER, PH OF OCEAN, PHOTOSYNTHESIS

FISSION WATER REACTORS:
CONCERN: USE OF IRREPLACABLE U-235 "SEED - CORN" - ONLY 1-2% EFFICIENCY FOR RECOVERING FUEL'S HEAT CONTENT
QUESTION: FUEL AVAILABILITY AT LOW COST

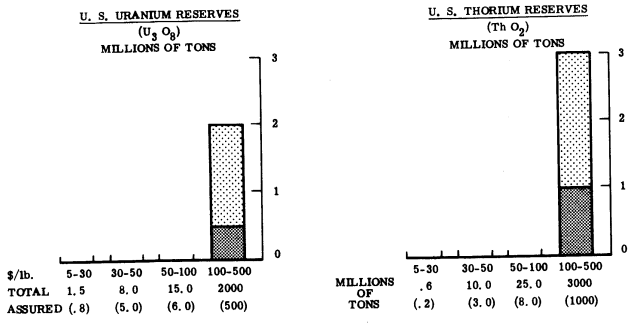


Figure 11

"INFINITE" ENERGY SOURCES

MAJOR:

FISSION BREEDER REACTORS:
QUESTION: FISSION PRODUCTS, SAFETY, AND RADIOECOLOGICAL CONCENTRATION PROCESSES, PROLIFERATION OF NUCLEAR MATERIAL

SOLAR ENERGY:
QUESTION: TECHNOLOGICAL ABILITY TO ECONOMICALLY AND EFFICIENTLY CONCENTRATE THE LOW RADIATION ENERGY DENSITY

FUSION REACTOR:
QUESTION: ADEQUATE SCIENTIFIC UNDERSTANDING OF PLASMA PHYSICS (CONFINEMENT AND SCALING LAWS)

MINOR:

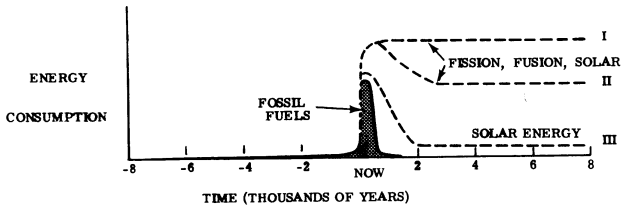
OTHER ENERGY SOURCES:
INSUFFICIENT TO MEET FUTURE DEMANDS

	WORLD POWER CAPACITY THOUSANDS OF MW
WATER	2,900
TIDAL	1,100
GEOTHERMAL	10
WIND	NEGLIGIBLE

BUT: WORLD ENERGY REQUIREMENTS = 30,000 BY YEAR 2000

Figure 12

THE GREAT TRANSITION



THREE TRAPS:
1. POPULATION (FOOD)
2. ENTROPY (RESOURCES, ENERGY, POLLUTION)
3. WAR (HUMAN NEEDS AND BEHAVIOR)

THREE ASSUMPTIONS
I. SUCCESSFUL CONTROL - AVOIDANCE OF TRAPS
II. SERIOUS OVERSHOOT OF POPULATION - TEMPORARY STATE OF CHAOS
III. SERIOUS FOOD, RESOURCES, AND ENERGY SHORTAGES - CONFUSION AND CHAOS - NUCLEAR WAR

Figure 13

brought under control, the grandchildren and great-grandchildren of those now 25 years old will have to cope with a world of about 19 billion people, of which 16 billion will be in underdeveloped countries.[42] Over the next 30 years, however, there appears to be only a very small probability that significant changes can be made in the projected population expansion. The difference between the high and low figures for the world population in 1985 is only 385 million persons, about the same as the probable range of uncertainty in the projected population of Mainland China in 1985. By the year 2000, the high estimate for world population is 7.15 billion persons and the low estimate is 6 billion persons.[43]

The period under consideration, i.e., up to the year 2020, covers the steep rise of the transient. This period of rapid growth and change is considered to be the most abnormal in human history. It represents one of the greatest ecological and biological upheavals known in geological history.[30] The use of auxiliary energy is a major contributor to this upheaval. Nevertheless, abundant energy will be needed to maintain control; yet the choice of energy sources is quite limited. Fossil fuels can represent only an intermediate step in the transition to ultimate dependence upon large-scale use of breeder reactors, controlled fusion energy and solar energy.

If civilization is to survive this transition and advance, it must avoid the three traps listed in Figure 13.[44] The use of the fusion torch in conjunction with controlled fusion power offers a potential solution to the entropy trap in materials–i.e. man's exhaustion of nature's stored resources. The availability of abundant cheap energy and

sufficient raw materials would be a significant factor in alleviating the stresses and hence providing the time necessary to avoid the other two traps.[45]

The following discussions of waste products and raw materials supplies are intended to give the dimensions of the entropy trap we are entering into. The discussion of thermal effects shows that although we use auxiliary energy to provide a better life and overcome problems, we must strive not to permit a portion of that energy to be misdirected and thereby create new problems.

B. WASTE PRODUCTS

By the year 2000, the solid wastes produced per person in the United States will rise to about 6.8 pounds/day as shown in figure 14.[46,47] Over the 35 year period from 1965-2000, almost 10 billion tons of solid refuse will have been accumulated in the United States as shown in Figure 15.[47] If this was all *compacted* and disposed of by sanitary landfill, it would require burial to a depth greater than 10 feet in a land area the size of the State of Delaware. If a burial depth of 20 feet were used, the land area could be reduced to the size of the state of Rhode Island. At the cost of one dollar per cubic foot[3] for sanitary landfill (reported costs in Los Angeles) this would require a total investment of over a half trillion dollars. The average composition of municipal refuse is given in Figure 16.[47]

To the solid wastes of municipal refuse, we must add a problem which is particularly important from the aesthetic and utilization of raw materials viewpoint. By 1965, automobiles, (and other consumer durables) were being junked at a rate so great, that this has become a problem of serious public concern. Between one-third and two-thirds of the metal content of the automobile usually finds a market as relatively high-grade scrap. The principle problems are encountered in marketing or disposing of the stripped bulk. This is the result of the commingling of copper and other contaminants metals with iron and steel. The effect is to render the metals difficult and expensive to separate. This degrades the quality of ferrous automotive scrap and discourages its use.[48]

Solid wastes of industrial origin comprise another category of major magnitude.[49] Fortunately, significant amounts of such wastes are salvaged and recycled. (The secondary materials industry is estimated at 5-7 billion dollars a year.) The introduction of new materials will aggravate the problem of industrial wastes in the future.

REFUSE PRODUCTION PER PERSON IN THE U.S.

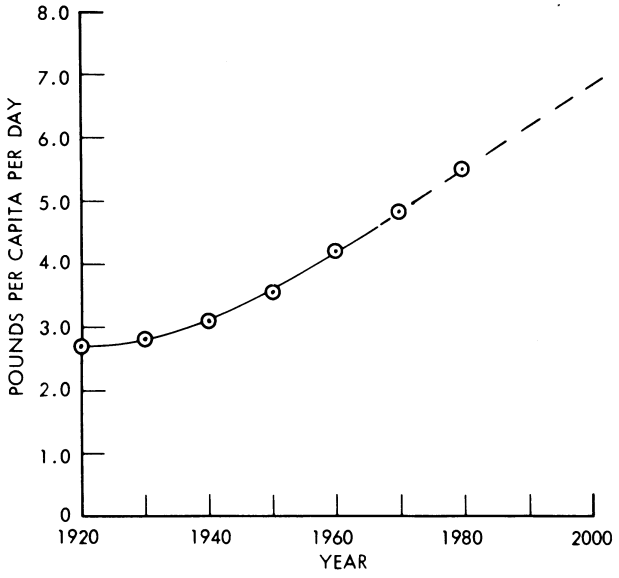


Figure 14

LAND AREA REQUIRED IF ALL REFUSE PRODUCED IN THE UNITED STATES IS DISPOSED OF BY SANITARY LANDFILL

YEAR	ACCUMULATED SOLID WASTE (10^9 TONS)	SQUARE MILES OF LAND AT FINAL DEPTHS OF(1) 10 FT	15 FT	20 FT
1965	0	0	0	0
1970	0.85	187.5	140.6	93.8
1975	1.84	406.3	304.7	203.1
1980	2.99	671.9	515.6	343.8
1985	4.31	968.8	726.6	484.4
1990	5.82	1296.9	984.4	656.2
1995	7.55	1687.5	1265.6	843.8
2000	9.49	2125.0	1593.8	1062.5

(1) BASED ON FINAL COMPACTION TO DENSITY OF 32 LBS/FT^3.

Figure 15

AVERAGE COMPOSITION OF MUNICIPAL REFUSE (% BY WEIGHT)

RUBBISH (64 PER CENT)	
PAPER, ALL KINDS	42
WOOD AND BARK	2.4
GRASS	4.0
BRUSH	1.5
CUTTINGS, GREEN	1.5
LEAVES, DRY	5.0
LEATHER GOODS	0.3
RUBBER	0.6
PLASTICS	0.7
OILS, PAINT	0.8
LINOLEUM	0.1
RAGS	0.6
STREET REFUSE	3.0
DIRT, HOUSEHOLD	1.0
UNCLASSIFIED	0.5
FOOD WASTES (12 PER CENT)	
GARBAGE	10.0
FATS	2.0
NON COMBUSTIBLES (24 PER CENT)	
METALS	8.0
GLASS AND CERAMICS	6.0
ASHES	10.0
	100.0

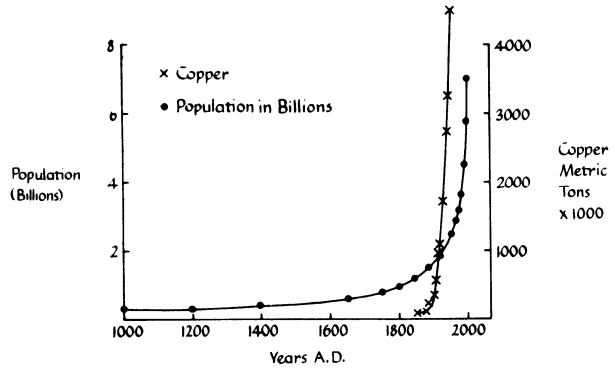
Figure 16

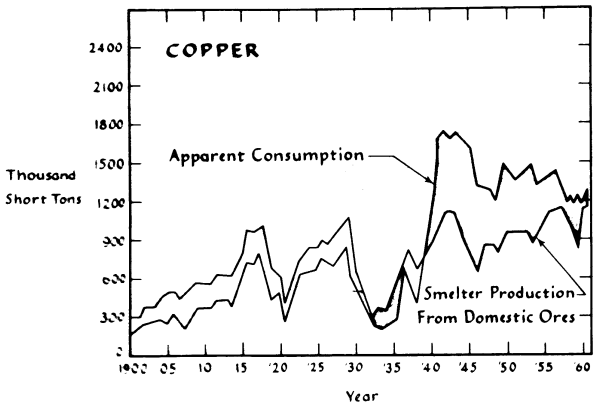
Large quantities of waste material will result from the mining of solid fuels, metals, and nonmetallic minerals. At the present time almost 60 percent of the material mined in the United States ends up as waste rock or mill tailings discarded at the site of operation.[49] As the demands for raw materials increase and the better grade material resources of the world are depleted, a higher and higher percentage of the materials mined will be mining wastes.

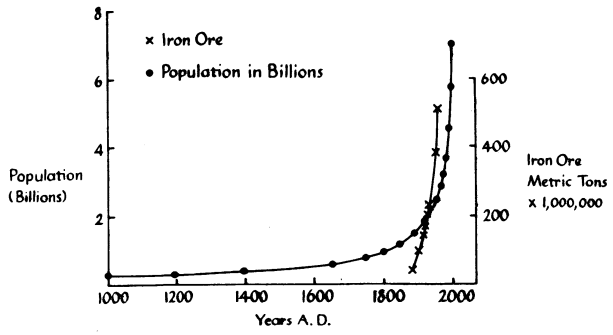
C. RAW MATERIAL SUPPLY

A report by the Committee on Pollution of the NAS-NRC states that "the ultimate goal (for solid waste disposal) should be complete re-cycling of all materials required by the urban areas. Until such ideal systems can be developed, it appears inevitable that portions of the landscape must be given over to waste-disposal requirements. Ultimately, however, more and more attention must be given to realization of the ideal; it is manifestly impossible for the human species to continue present rates of population increase, present rates of increase in per capita consumption of goods; and simultaneously maintain an environment in which waste products do not become ultimately totally inhibitory to life."[46]

But there is another problem intimately related to the buildup of wastes that is catching up on us from behind, because it is largely unobserved and unheeded—the peril of mineral shortages. A few mineral commodities, for example, iron and aluminum, exist in sufficient quantities to maintain the industries of the world and to permit considerable expansion. A few other commodities, such as mercury, tin, and silver, are already pressed to maintain their current production and markets; their prices to consumers are rising. Between these two extremes lie the great majority of mineral products. They are present in the earth's crust in amounts sufficient to satisfy current demands and to allow for moderate expansion. By the year 2000, the mineral reserves of the world will have great difficulty keeping abreast of the rapid rise in population. For metals like copper, lead, zinc, tin and many others the outlook will become precarious. Figures 17, 18 and 19 show the effect of increased population on ore consumption *without* considering increased per capita consumption. The lower portion of each figure shows the increasing dependence of the United States on foreign sources of ores.[50] A study of the seriousness of this problem by C. F. Park, Jr. of Stanford University concludes that: "Of the 100 minerals most important to its industries, the United States possesses within its national boundaries adequate supplies of only about a dozen. It is today a have-not nation where raw materials are concerned."[51]







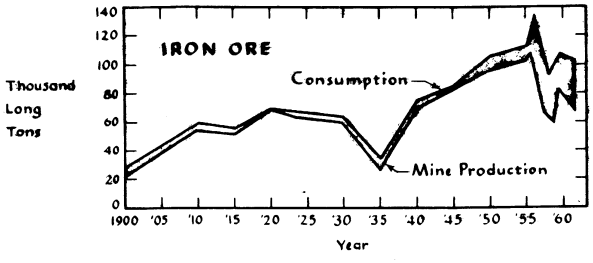
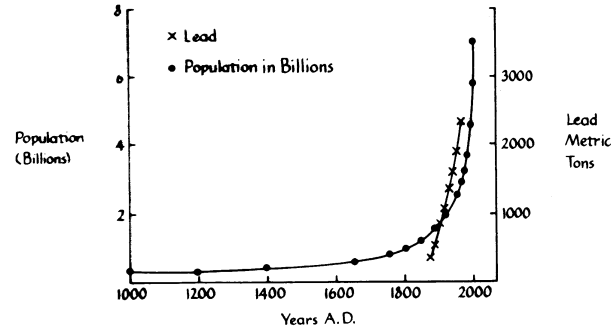


Figure 17



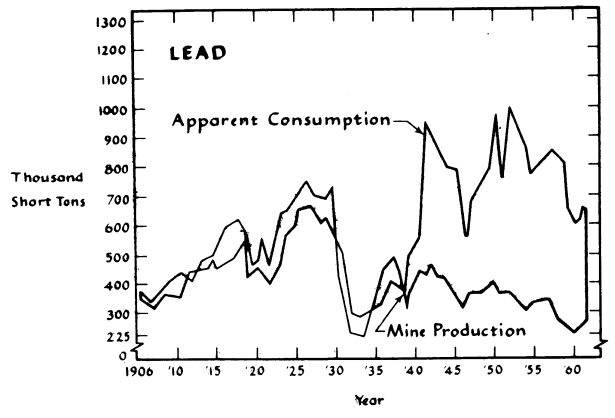


Figure 19

For planning purposes, commodity statements on over 80 items are maintained and continually updated by the Bureau of Mines to identify how the national interests might be influenced by probable changes in emerging mineral supply-demand relationships. The current compilation projects that the U.S. demand will *exceed* U.S. production in the year 2000 for about 80 percent of the *basic elements* listed (excluding fuels, common gases, and items such as gravel.)[52]

The reliability of foreign mineral sources is difficult to assess. Besides the possibility that supplies may be interrupted by war or unfavorable political developments, we must recognize that the less developed nations are no longer willing to exist as mere suppliers to the developed nations that enjoy the advantages of advanced industrial economies. The magnitude of the problem by the year 2000 can be assessed by looking at the change in wealth and population projected for the developed and less developed countries in Figure 20.[53] It would take only a small increase in per capita consumption to change the tone of current estimates of mineral resources from optimism to pessimism.[50]

Even now with a world population of about three billion people, a very slight rise in living standards can greatly increase consumption of minerals. For example, "it has been estimated that an increase of 1 pound per year of per capita consumption of copper would immediately require a 36 percent increase in world copper production."[50] Thus, near the base of potential pyramiding troubles in international relations are resource needs.

GROWTH OF WORLD POPULATION AND WEALTH

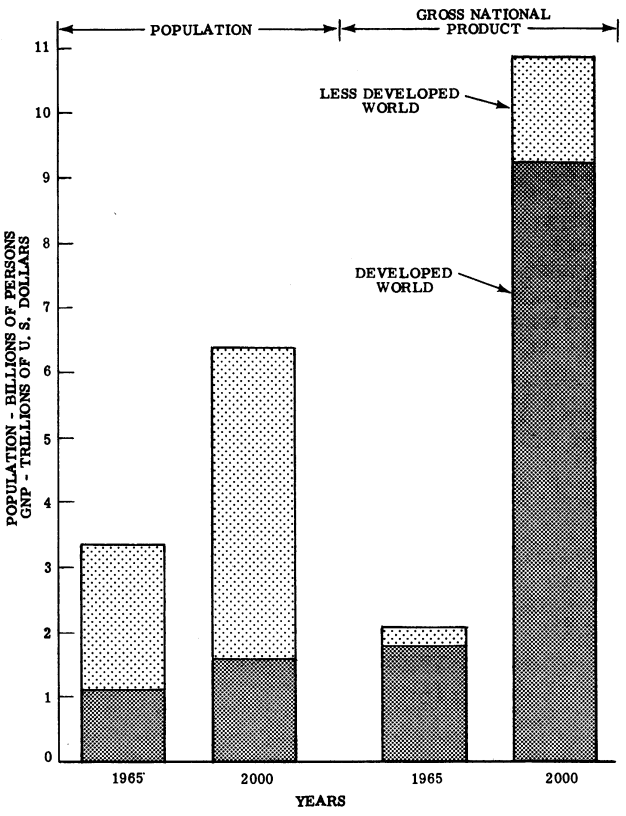


Figure 20

D. THERMAL EFFECTS

Changes in the thermal environment due to waste heat is causing an ecological crisis.[54] Yet, thermal pollution is nothing more than energy in the wrong place and thus it is directly related to power plant

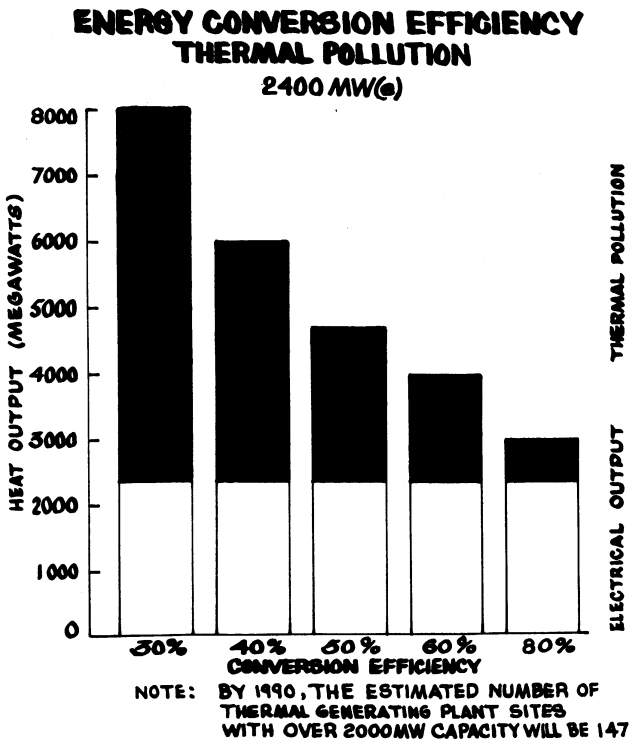


Figure 21

efficiency. Figure 21 shows the effect of increased power plant efficiency in reducing thermal pollution.

At present, the thermal efficiency of electric power plants are essentially set by the temperature limits of solid materials, i.e., by the wall materials, the melting point of the nuclear fuel and its cladding, the blade temperature of gas turbines, or the electrodes of MHD converters. Studies of DT fusion power plants that use the common heat energy cycle for energy conversion give a good thermal efficiency of around 60 percent.[8] Yet, this is not an optimum match of an energy converter to a fusion energy source since such converters require the fusion energy which is at over 50,000,000°C to be degraded to temperatures of less than 2000°C because of materials' limitations. With an advanced type of energy converter, controlled fusion offers the possibility of removing the limitations that solid materials have always set upon the efficiencies of electric power plants. The fusion fuel, which is in the form of a very hot plasma consisting of charged particles, can interact with the electromagnetic fields. Thus, the kinetic energy of the charged particles in a fusion reactor can in principle be directly converted to electrical energy without contact with material walls. The cycle efficiencies for such conversions would be close to 100 percent. Possible direct energy converters include inductive magnetoplasma-dynamic converters,[55] a staged electrogasdynamic converter,[56] and by plasma expansion against the magnetic field.[57] Using the D-He^3 fuel cycle, efficiencies of from 80 to 90 percent appear achievable.[58,56]

Through the use of the fusion torch described in the next sections new possibilities for energy conversion become available. The kinetic energy in the fusion plasma could be directly (a) stored as chemical energy by the breaking up of molecular bonds; (b) transferred as ultraviolet radiation for the bulk heating of fuel cells used to generate electricity; (c) transformed into portable energy via plasma chemistry; or if it is waste (d) dissipated as optical radiation to the atmosphere thereby avoiding local thermal effects.

II. TECHNICAL ASPECTS OF THE FUSION TORCH

The "Fusion Torch" concept is the use of a thermonuclear plasma source (from either an energy producing fusion reactor or from a fusion plasma device that uses energy) as the starting point for industrial processes that use one or more of the unique properties of such plasmas. The kinetic energy of charged particle motion may be converted into (a) radiation (optical, ultraviolet or soft x-ray) or (b) the dissociation and/or ionization of any solid, liquid, or gas. This section will describe the relevant physics of the interactions in a fusion torch so that quantitative discussions of specific applications can be described in later sections.

A general schematic of a possible fusion torch configuration is presented in figure 22. Plasma is generated in region I, with temperatures of T_e for the electrons and T_i for the ions. (It may be advantageous to run a reactor with these temperatures unequal)[8]. The electron and hydrogen ion densities are assumed equal and of magnitude n_e. The plasma would be transferred to region III, the interaction zone, via region II the connecting region. It is in the interaction zone that the processing would take place. (It should be noted that we are not suggesting that material be injected in the plasma source itself.) The plasma entering the connecting region could consist of plasma lost from the reactor due to the nature of containment *or* could be intentionally fed into the chamber by suitable adjustments to the intensity and shape of the magnetic fields.

THE FUSION TORCH

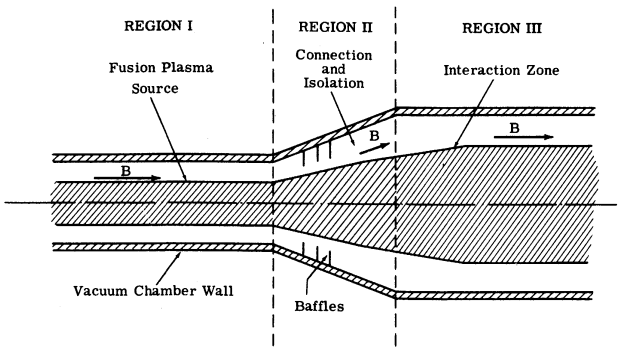


Figure 22

A. CONSERVATION EQUATIONS

A complete analysis of a given fusion application would comprise a solution (including boundary conditions) of the equations of conservation of mass, momentum and energy for each species of matter involved. We list these equations, and then, in the discussion of specific interactions, we point out the dominant processes. (For example, when a solid is injected in region III, we show that the bulk of the plasma energy is transferred to the solid via a shock wave.) The conservation equations are listed below.

The letters s and κ are used to identify specific atomic or ionic components of the plasma. A complete set of equations, including boundary conditions, would be needed for each species if a complete solution to a given problem is desired. (For example, if xenon were injected into a hydrogenic plasma in region III, then one would have to follow the time dependent behavior of H^+, e, Xe, Xe^+, Xe^{++}, etc.)

1. Conservation of Mass

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial}{\partial x_j}(\rho_s \vec{u}_j^s) = w_s \qquad (1)$$

where $\rho_s = m_s n_s$

m_s = mass of particle s

n_s = number density of particle s

w_s = net rate of mass production (or elimination) of s per unit volume

2. Conservation of Momentum

$$\frac{\partial}{\partial t}(\rho_s \vec{u}_i^s) + \frac{\partial}{\partial x_j}(\rho_s \vec{u}_i^s \vec{u}_j^s) =$$

$$\frac{\partial P_{ji}^s}{\partial x_j} + n_s Z_s e\,[E_i + (\vec{u}_s \times \vec{B})_i] + P_i^{s\kappa} \qquad (2)$$

where $P_{ji}^s = -\delta_{ji} P_s$ + viscous terms

P_s = partial pressure of species s

$= n_s k T_s$

E_i = Electric field strength

B = Magnetic field strength

$P_i^{s\kappa}$ = Momentum transfer in direction i from collisions with non identical species

i,j,k = coordinate designations

3. Conservation of Energy

$$\rho_s \frac{D}{Dt}\left(e_s + \frac{P_s}{\rho_s} + \frac{\vec{u}^s \cdot \vec{u}^s}{2}\right) = \rho_s \frac{D}{Dt} h_o \qquad (3)$$

$+ \dfrac{\partial P_s}{\partial t}$ — a pressure term (a)

$+ \eta j^2$ — ohmic heating, where η is the resistivity (b)

$+ \rho_s \epsilon_{s\kappa} \nu_{s\kappa} (\vec{u}_s - \vec{u}_\kappa)^2$ — energy transfer due to viscosity where $\epsilon_{s\kappa}$ = efficiency of transfer $\nu_{s\kappa}$ = collision frequency (c)

$+ \dfrac{3}{2} \sum_{s \neq \kappa} \dfrac{\rho_s}{m_s} \dfrac{\rho_\kappa}{m_\kappa} \xi_s k T_\kappa$ — energy gain of s due to transformation of κ where $\xi_{s\kappa}$ = transformation rate (d)

$-\sum_{s\neq\kappa}\frac{\rho_s}{m_s}\frac{\rho_\kappa}{m_\kappa}W_{s\kappa}\xi_{s\kappa}$	energy loss of s due to transformation of κ where $W_{s\kappa}$ is transformation potential	(e)
$-\frac{3}{2}\frac{\rho_s}{m_s}k\sum_{s\neq\kappa}[f_{s\kappa}\nu_{s\kappa}(T_s-T_\kappa)]$	energy loss due to elastic collisions between species s and k	(f)
$-\frac{3}{2}n_s k f_{exc}\nu_{s\kappa}T_s$	energy loss to excitation (when s designates the electron)	(g)
$-\nabla\cdot\vec{Q}$	Thermal transfer	(h)
$-\Pi$	radiation losses, such as cyclotron, bremsstrahlung and others.	(i)

where e_s = internal kinetic energy of s

h_o = stagnation enthalpy

B. CONNECTION REGION

Region II, the connection region, has two functions. The first is to transfer the highly pure hydrogenic plasma from its source into the interaction region. This transfer must take place with a minimum of radiative and particle loss. It can easily be shown that for connection lengths on the order of meters and plasma flow velocities on the order of 10^5 cm/sec that the change in plasma energy due to synchrotron and bremsstrahlung radiation is negligible for densities less than $10^{17}/cm^3$.

A second role of the connecting region is to isolate the plasma source from the interaction region. Isolation of the plasma source from non-hydrogenic ions in the interaction region can be accomplished if the following equation is satisfied: (equation one with $w_s = 0$).

$$\vec{u} > D\frac{\vec{\nabla}n_s}{n+n_s} \qquad (4)$$

where $\vec{u}$ = flow velocity of plasma in region II

D = diffusion coefficient parallel to B

n = number density of plasma

n_s = number density of other species

The above expression describes the requirement that the bulk flow velocity of the fusion plasma must be greater than the upstream diffusion velocity of other species. (Neutral atoms could be captured by baffles in regions not containing plasma.) Observational data on diffusion parallel to a magnetic field in a plasma with high flow velocity shows that this condition can be satisfied.[60]

Isolation of the interaction region from neutrons produced in the source would be important in the case of a D-T cycle, which produces a significant flux of 14 MeV neutrons. Such isolation can be accomplished by transferring the plasma to an interaction region located in the shadow of the reactor's lithium blankets. A possible geometry is shown in figure 23. Blanket laminations could be located as shown to prevent reflection of neutrons in the channel. Tuckfield and Scott have transported a fusion plasma around a 90 degree turn using appropriately shaped magnetic fields.[91] Of course, an energy consuming ultra high temperature plasma device need not produce neutrons.

C. CONTROL OF PLASMA FLOW PARAMETERS

Control over plasma density, temperature and flow velocity will be important in all regions of the fusion torch. In region III, such control can aid in providing plasma conditions suitable for the particular application desired. Later in the processing cycle it could be important to maintain a given plasma temperature while the plasma density and composition changes (i.e. "selective recombination"). If the stagnation enthalpy (h_o in equation 3) is held constant then such control can be achieved (in much the same way as nozzles control the parameters in high temperature flowing gases). A decrease in flow velocity leads to an increase in temperature. Uchida et al have studied such expansion and compression in experiments in which a theta pinch plasma was guided in a mirror field.[59] It appears that the necessary control over plasma parameters can be achieved.

D. PLASMA – GAS INTERACTION

The injection of a gas into a fusion plasma leads to a loss of plasma energy through the terms on the right hand side of equation 3. It has been shown both theoretically[69] and experimentally[65,70] that excitation radiation from highly ionized atoms (part g of equation 3) is the dominant loss mechanism when a small percentage of high Z atoms are included in a fusion plasma. Analysis of such excitation radiation has been carried out by Burton and Wilson using the "time dependent coronal" model of a plasma.[70]

We assert that this characteristic of a fusion plasma makes it possible, by appropriate choice of high Z gases, to transform the plasma kinetic energy into ultraviolet and soft x-ray radiation at discrete frequencies. Production of ultraviolet and soft x-ray radiation was one of the reasons it took so long (see figure 1) to achieve fusion temperatures in laboratory plasmas. Thus, it has already been proven that a plasma can transform its energy into a radiation field.

The degree of control one has over the intensity and frequency of such radiation must be studied in more detail. While commercial sources of ultraviolet radiation use low temperature plasmas,[86] fusion plasmas have barely received study for such uses.[66] Three factors are favorable to achieving control over the emission frequency. First, the source is initially a pure hydrogen plasma–i.e. the initial conditions are well known. Second, the flux of high Z atoms can be controlled independently. Thus, a flux could be chosen that would result in the conversion of the bulk of the plasma kinetic energy to radiation *before* a specified ionization level is reached. Third, although the excitation radiation can occur at many discrete frequencies for each level of

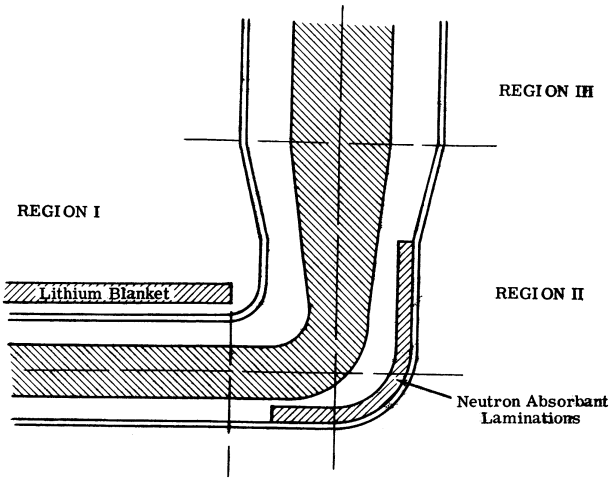


Figure 23

ionization, in practice, just a few of lines (usually the resonance lines) are strong.

A series of experiments to determine the control one could achieve would be desirable. Many different existing fusion devices could be used for such studies. Aluminum is used as an example in section IV.

E. PLASMA – SOLID INTERACTION

The vaporization and ionization of a solid injected into a fusion plasma will undoubtedly be rapid due to the extremely high internal electron energy flux. Spitzer et al have analyzed the interaction of a solid with such a plasma as an ablative process.[72] While some ablation will occur, we show that it is more likely that the solid will be vaporized and ionized by a shock wave induced by the absorption of the plasma energy in a very thin surface layer. The heat flux term $(\nabla \cdot Q)$ in equation 3 is shown to be the dominant plasma energy loss term. Thus, the plasma kinetic energy can be efficiently used in the transformation of a solid into its elemental ionic constituents.

The shock vaporization of solids is possible in a fusion plasma but is not possible in present day commercial plasmas. In conventional commercial plasmas (D.C. arcs and argon discharges) it has been found very difficult to vaporize and ionize solids.[71] This is due primarily to the fact that ablative cooling can not be fast enough to permit the complete vaporization of the material on time scales characteristic of the residence time of the solids in the hot portion of the arc. A high value for energy flux within a D.C. arc is 10^4 joules/cm^2-sec. For comparison, a thermonuclear plasma with $n = 10^{15}/cm^3$ and $T_e = 10^4$ev has an energy flux, defined by the equation:

$$F = 2kTn\,(kT/2\pi m_e)^{1/2} \qquad (5)$$

of 8.4×10^9 joules/cm^2-sec. Equation 5 is plotted in figure 24.

Such energy flux levels are, interestingly enough, similar to some laser produced plasma experiments. For example, in a typical set of experiments at United Aircraft,[73] the laser energy flux ranged between 6×10^7 joules/cm^2-sec and 10^{10} joules/cm^2-sec. Dawson originally suggested a shock interaction as the initial interaction leading to vaporization when such energy flux is incident on a small particle.[74] Lubin seems to have verified this hypothesis.[75] Caruso and Gratton have studied shock aspects of the general laser interaction problem.[76]

The initial interaction of a fusion plasma with a solid would obviously be similar to the laser case, as the energy flux is of the same magnitude and is also deposited in a thin surface layer. The condition necessary for propagation of a shock wave in a solid is:

$$F > v_s E_v \qquad (6)$$

where F = energy flux

v_s = shock speed in solid

E_v = energy needed to vaporize per unit volume

The line defined by this equation for the typical values $v_s = 10^5$ cm/sec and $E_v = 10^4$ joules/cm^3 is shown in figure 24. Above the line, shock vaporization will occur. Below it, ablation will be dominant. We must also show that sufficient energy can be transported through the plasma to the particle in a short enough time to allow complete vaporization. This requirement results in the condition defined below for a spherical solid of radius r (derivation in appendix I):

$$1.3 \times 10^3\, r\, \frac{E_v^2}{n T_e^{9/2}} < \frac{1}{v_s} \qquad (7)$$

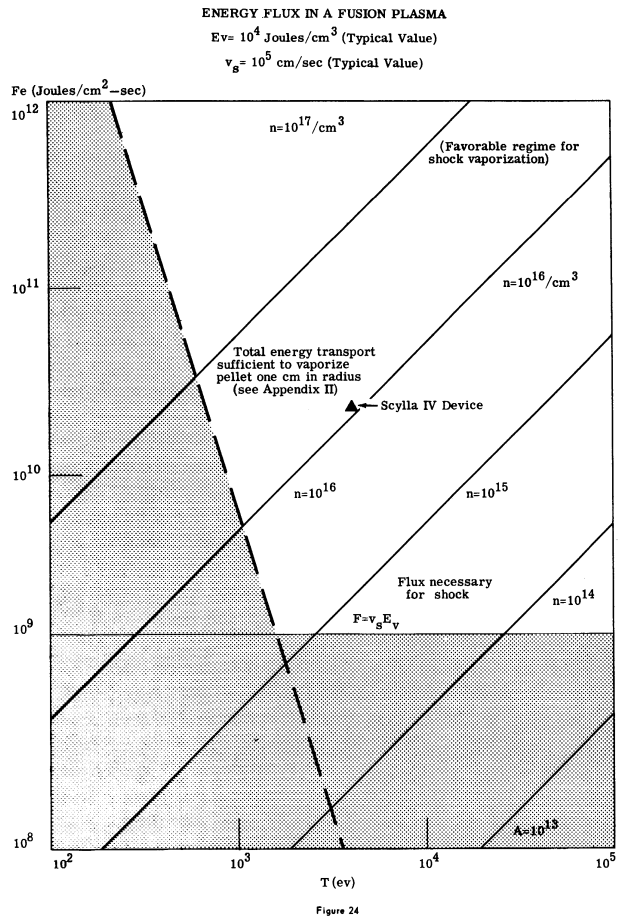


Figure 24

where E_v is in joules/cm^3

n is in number/cm^3

T_e is in kev

The line defined by this equation is shown in figure 24 for the values of E_v and v used above (for r = 1 cm). To the left of this line it would not be possible for energy to reach the solid fast enough to completely vaporize it. The shock wave would probably shatter the object in this case.

Sheath effects have been considered by Spitzer et al.[72] They find that secondary emission is important in determining the sheath conditions and that the flux of energy delivered to a surface is comparable to that of equation 5. Their analysis did not include shock effects however, and a more complete analysis is in order.

The hydrodynamic expansion of the shock heated solid and its subsequent mixing with the plasma is not treated here. By suitable control of the plasma flow and the feed rate of solid it should be possible to have a low temperature plasma, composed primarily of ionic species characteristic of the solid, leave the interaction region.

As the shock heating capability of a fusion plasma has not been proven experimentally we suggest an experiment that could do this. The Scylla IV theta pinch device at the Los Alamos Scientific Laboratory produces a plasma with parameters (shown in figure 24) that could check the shock theory. Its total stored kinetic energy is 5×10^3 joules, thus allowing vaporization of one half cubic centimeter of the typical material. The Scylla IV produces a cylindrical plasma that is lost through its ends. Thus, either a thin foil or particles could be suspended in the plasma as it is lost.

III. WASTE PRODUCT ELIMINATION – RAW MATERIAL RECOVERY

In this section, we propose that the fusion torch be used to close the basic link from user back to resource. Waste products could be converted back to elemental form, thus simultaneously eliminating the problem of disposal of the waste product while providing a supply of basic raw materials for the ever-expanding world technological base.

When a solid is injected into the fusion torch, the interaction described in section II results in the transformation of an ultra-high temperature hydrogen plasma into a low temperature plasma composed of ionic species characteristic of the solid. As will be shown below, a variety of techniques can then be employed to separate the ionic species according to either atomic number or atomic mass. While not attempting to minimize the difficult technological problems of perfecting separation techniques, it is important to note that irrespective of a solid's chemical composition or mechanical properties, at most only 92 (the number of natural elements) ionic components need be considered. In most cases of practical interest this number would drop still further. (A tin can consists chiefly of Fe and Sn.) Thus, while many chemical or electrochemical techniques could be considered as alternative schemes for recovery of elements from waste products, the number of processes that would be needed would essentially equal the number of types of waste products. The fusion torch offers the possibility of handling *all species* in one central recovery plant.

It is instructive to determine the amount of energy needed to process a pound of material in the interaction region. This energy requirement is given by the following expression:

$$C = 8.6 \frac{\bar{\epsilon}}{A} \qquad (8)$$

where $\bar{\epsilon}$ = Energy needed/atom in eV

A = Mean atomic weight/atom

Thus we see that the energy consumption per pound decreases as the atomic weight increases. (The energy needed to ionize an atom usually lies between 5 and 15 eV and is to a large extent independent of mass.) This equation is plotted for various values of ϵ in figure 25. Even at 5 mils/kwt–hr. the energy requirements for processing with the fusion torch can be rather low.

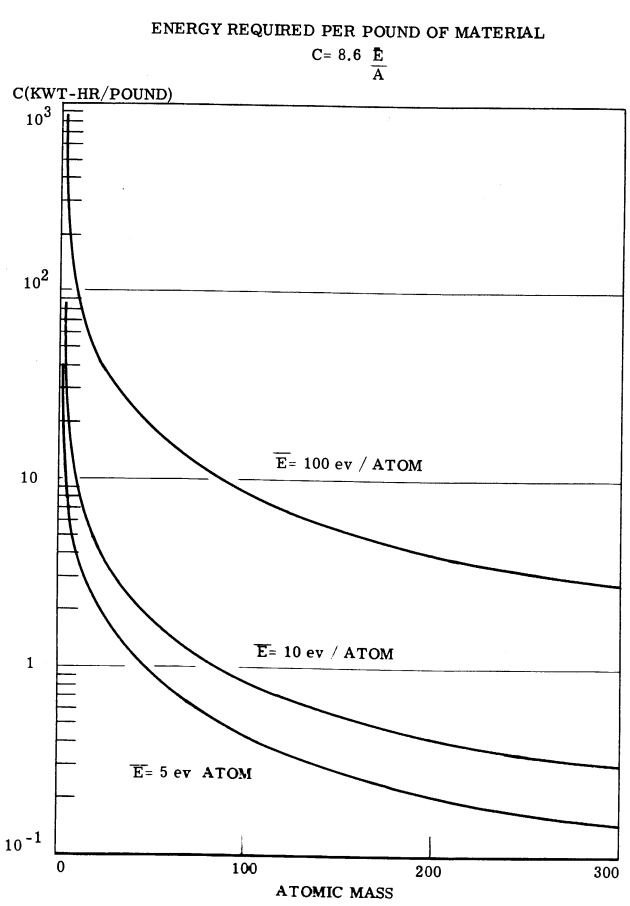


Figure 25

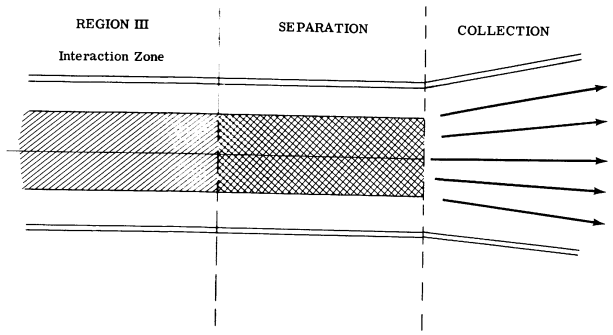


Figure 26

A. SEPARATION TECHNIQUES

The preparation of a plasma composed of the ionic species of an arbitrary solid was described in section II. It remains to show the advantage in preparing the solid in this manner for separation purposes, compared to techniques that apply electrochemical or chemical methods to the solid directly.

The plasma state puts a number of different techniques at one's disposal for separation. A diagram showing the interaction region, the separation region and a collection region is shown in figure 26. Figure 27 is a brief listing of possible separation techniques.

1. Electromagnetic Separation

Electromagnetic separation is one of the most general techniques one might consider.[77,78,79,80] Isotopic separation has used electromagnetic processes for a number of years. Cost of *isotopic* separation has been large but has dropped significantly during recent years due to advances in plasma physics and beam handling.[80] (In the Calutrons at ORNL for example.)[80] In the case discussed here we are primarily interested in separating a few elements with *large mass* differences. For example, if the torch were being used to reduce an ore, such as FeO_2, then the separation system would need to separate iron with mass 57 from oxygen with mass 16. All in all, the advancement in plasma physics, coupled with the reduced requirements on the degree of mass differentiation required, makes electromagnetic separation a prime candidate for use with the fusion torch. (One might find that some ideas on electromagnetic separation developed during World War II could be dusted off and be found attractive for this application.)[78]

The capital cost of the separation section is estimated to be large compared to other ideas outlined in figure 27. Some energy would have to be expended in the separation process, making the energy needed per pound in the separation section comparable to that in the interaction region.

SEPARATION TECHNIQUES

SEPARATION TECHNIQUE	RELATIVE CAPITAL COST	AREA OF APPLICATION	PRESENT STATUS
ELECTROMAGNETIC	LARGE	ALL	CALUTRON WORKS
FAST QUENCH	SMALL	ORE REDUCTION AUTOMOBILE METAL SCRAP PLASTICS ALLOYS	MUCH EXPERIENCE IN PLASMA CHEMISTRY
SELECTIVE RECOMBINATION	MEDIUM	SAME AS ABOVE	LITTLE WORK
CHARGE EXCHANGE	SMALL	ALL	SOME BASIC WORK
OTHERS			

Figure 27

2. "Quench" Techniques

A technique that is especially suited to the fusion torch is to "quench" the plasma flow stream rapidly. T. B. Reed has described the principal of the fast quench (which is of considerable importance in plasma chemistry) as follows.

"Spectroscopic studies of stars show that the outer atmospheres of stars in the 2000-6000°K region are rich in various molecules and free radicals. If such an atmosphere is slowly cooled, the final products will be the most stable molecules at 500-1000°K, depending on where the approach to equilibrium is stopped for kinetic reasons. Often the most stable species are solids. However, if such an atmosphere is quenched as rapidly as possible, say in a few microseconds, there is a strong tendency for it to form simple gaseous molecules, no matter what their stability, since the nucleation and growth of solids require many more collisions than do the formation of gases. In this case molecules may form that are not stable at room temperature or at plasma temperatures with respect to their solid elements, but are stable with respect to the free radicals and molecular fragments existing at the plasma temperatures. This preference for forming gaseous molecules over solid ones may be called the "condensation barrier." It refers to the tendency to form the simplest rather than the most stable molecules from molecular fragments at high quenching rates . . ."

A large variety of means have been used to quench high temperature plasmas, such as the injection of gases into the flow stream. It should be noted that there is sufficient control in region II to produce the plasma streaming into the separation region in a manner such that it is at a temperature in the 2000 to 6000 degree range. In fact, at this stage in the processing, it would not even be necessary to support the plasma pressure via a magnetic field–conventional piping could be used.

The capital cost of this type of separation would be very low and no energy would be needed per pound of material. This process seems especially suited to such applications as (a) ore reduction and beneficiation (particularly high grade ore that contains impurities that are difficult to separate by conventional processes), (b) recovery of elements from eutectics, alloys, and low grade metal scrap, and (c) elimination of plastic and paper waste products.

3. Selective Recombination

"Selective recombination" could also be considered for the above class of applications. "Selective recombination" would involve holding the plasma temperature and density constant at a set of conditions that would be favorable to the recombination of a desired species which would be collected on the walls while the remaining species are piped away. This means of purification, based on ionization potentials, received initial study in a paper by P. Schmidt, et al.[81]

There would be some capital cost with such a technique because of the need to provide for control of the flow stream parameters in the separation region. The energy needs per pound of material would obviously be small however.

4. Charge Exchange

Charge exchange has been suggested as a separation technique.[82] This idea is based on the rather large differences in charge exchange cross sections between different atomic species. A typical set of charge exchange cross sections is shown in figure 28. The idea here would be to spray beams of a gas at the flowing plasma stream and replace the desired ion in the plasma with the injected gas atom or molecule, and collect the desired species on the wall while the other species are piped away along the magnetic field. Much work on charge exchange cross sections has been performed, but we are unaware of any work applying it to separation of plasmas.

The capital and unit costs would be rather low for such a technique. Such a process might be especially suited to separation of uranium from reactor fuel element material.[1]

Other techniques are easy to imagine and we have confidence that separation can be accomplished.

5. General Comments

The long term application of the fusion torch to re-cycling of raw materials in an essentially closed cycle city looks promising when the low cost and availability of a fusion power plant is coupled with what should be significant advances in our ability to control plasmas. On a shorter time scale, specific applications such as ore reduction, alloy separation and plastics elimination could be considered using modified plasma technology that is available at the present time.

Some interesting figures should be noted. An "all" electric city of 10,000,000 people, by the year 2000 will need 140,000 megawatts of electrical capacity.[30] If just 10,000 megawatts were used in a fusion torch then somewhere between 2,700 and 27,000 *tons* of material could be processed per day. This would involve the collection and removal of large volumes of material from the collection regions. We are thus talking about large chambers and massive engineering development in the long range applications.

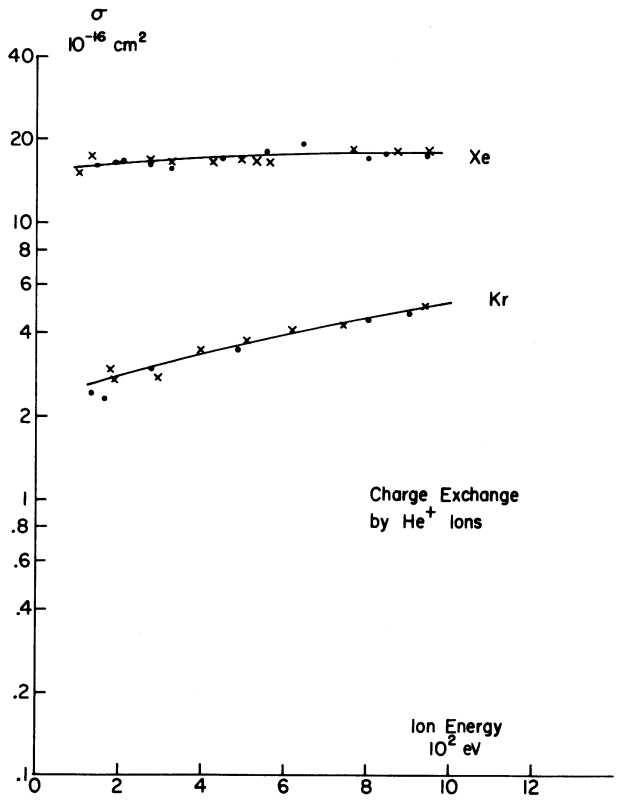


Figure 28

IV. TRANSFER OF PLASMA KINETIC ENERGY TO A RADIATION FIELD

The ability to transform plasma kinetic energy into ultraviolet or soft x-ray radiation with a high degree of efficiency and selectivity and transform that energy to a bulk fluid opens up the possibility of completely new approaches to such problems as desalination of sea water and treatment of raw liquid wastes. The number of possible applications is as great as the number of the uses of ultraviolet radiation.

1. Ultraviolet Energy Transfer to Water

It would be useful to describe a complete energy transfer scheme, including a discussion of ultraviolet window materials and absorption coefficients. We therefore treat the case of energy transfer from the plasma to water. The treatment is quite general however, and *any* substance whose absorption coefficient is finite and is known could be considered. In fact, it may not even be necessary to use a window, as substances could be injected into the vacuum chamber. (This would be especially true if uses of the soft x-ray region of the spectrum could be found.)

The general scheme is shown in figure 29. The ultraviolet radiation would be emitted from the plasma, pass through a suitable window and be absorbed in the flowing fluid.

In section II, we described the physics of excitation radiation. What remains is to show that it is possible to generate the bulk of the radiation in a frequency range that (a) can be transmitted through the UV window (b) can be absorbed in a meaningfully thick depth of water. (A penetration depth of a few mm in the fluid would obviously not lead to a practical system.)

The absorption coefficient α_1, of the window material and α_2 of the water are therefore important quantities to determine. The absorption coefficient of a synthetic quartz (designated x-246 by the developers) is plotted as α_1, in figure 30.[83] The absorption coefficient of clean water is plotted as α_2 in the same figure.[84] (Measurements such as this have not been reported for brine.) It is seen that at 1850 Å, the absorption depth in water would be one meter. At this same wavelength, a 1 centimeter thick quartz window would absorb only 1 percent of the incident ultraviolet energy.

The absolute flux of ultraviolet energy could be as high as megawatts/meter^2 . Although levels such as this are achievable, they are not necessary as one could regulate the rate of energy release by

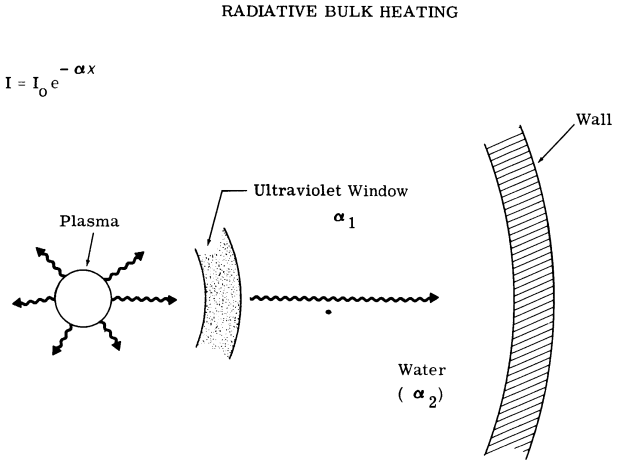


Figure 29

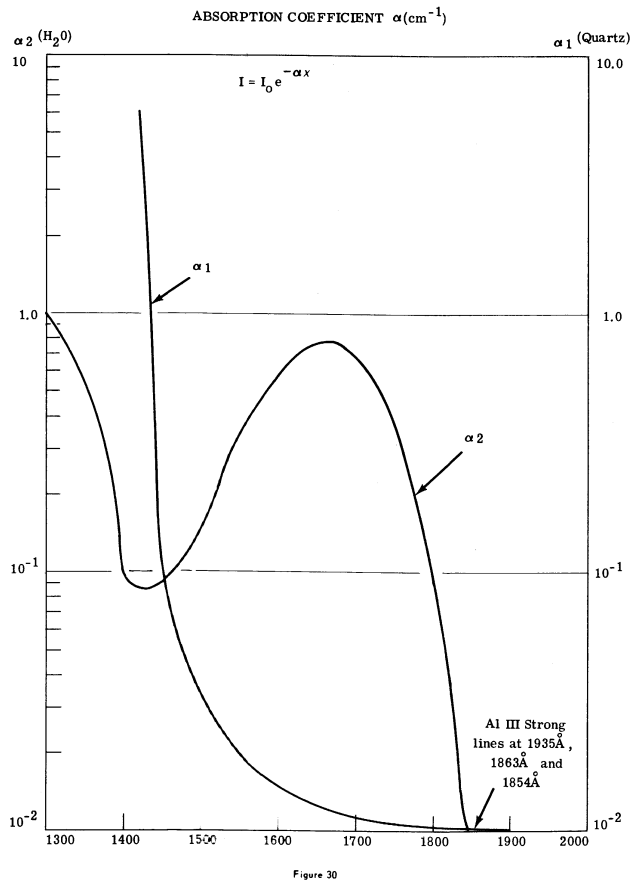


Figure 30

suitable adjustments in input flux of both neutral atoms and plasma in the interaction region. If it were desirable to run at very high flux levels suitable window materials (i. e. insensitive to high flux radiation) could most likely be developed. G. A. Yale has described recent work on the development of radiation resistant ultraviolet window material.[85] (One should note that the fluid need not be in physical contact with the window. The fusion torch could be used much like a light bulb to illuminate a large area of material.) Referring to figure 10, such illumination might be applied to algae culture.

It is difficult to predict the actual percentage of plasma kinetic energy that can be transferred into a given spectral line or group of lines. However, there are some guideposts we can use.

The quality of ultraviolet sources seems to have paralled the development of *plasma* sources. The best line ultraviolet sources are duoplasmatrons (a particularly high temperature arc.)[86] Some work has been done on the development of the theta-pinch (a fusion experimental device) as radiation sources, but the effort is small at the present time.[66]

We have listed three of the strongest ultraviolet lines of Al III on figure 30. As shown by Post, the energy lost to the higher excited states of high Z atoms imbedded in a fusion plasma can exceed the *total* lost to lower excited states.[69] If Aluminum vapor were injected at a rate sufficient to radiate away the energy of the plasma *before* the aluminum has reached its third ionization state, then up to 86 percent of the plasma kinetic energy could be converted into line radiation in the *wavelength* region from 1850 to 1935 Å. (The remainder would be emitted as Al I and Al II radiation.) A high degree of control of this process can be achieved by regulating the input flux of high Z atoms.

2. Applications (Desalination, Sewage Treatment, etc.)

This method of bulk heating appears to be an ideal method for matching an ultrahigh temperature primary energy source to heating of liquids. Besides the development of new desalination techniques based on bulk energy transfer by radiation, one could even consider the treatment of raw sewage and animal wastes. [87] (By use of the ultraviolet to either kill bacteria directly or as a means of generating copius amounts of ozone.)

On a near term basis, one could generate kilowatt and megawatt sources of ultraviolet using already developed technology. (It is interesting to note that in large theta pinch systems, if a quartz experimental chamber is used to surround the plasma, then sufficient ultraviolet radiation impinges on the surrounding air to generate a shock wave which can propagate towards the quartz–breaking it.)[88]

V. PLASMA CHEMISTRY

The fusion torch could be used to provide large volumes of highly reactive monatomic and ionic species. For example, in figure 31 we illustrate the production of monatomic species and their mixture with other gases to perform chemistry. In this range of applications, the fusion plasma is being used merely as a source of energy. The study of this type of plasma chemistry is already under development. The main contribution fusion plasmas could make here is to provide (a) large volume sources (b) higher initial temperatures in the reacting vessel than present capabilities allow and (c) initial conditions that are more well defined than in arcs.

As mentioned in the last section, radiation from the plasma could be used for photolysis and other UV applications.

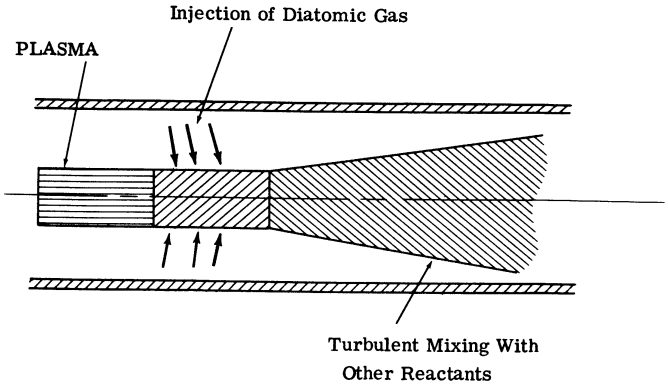


Figure 31

CONCLUSIONS

Proposed in this paper are new concepts for the application of ultra-high temperature plasmas now available in fusion experiments and eventually in controlled fusion reactors. The unique physical properties of a fusion plasma and their application to important problems of our industrial age are presented. Reviewed are (a) the critical importance of energy to an expanding industrial society, (b) the very limited number of major energy sources available to meet future needs, and (c) the possible requirement of an option among these should unforseen ecological and biological problems arise. Also, briefly discussed are the recent important scientific and technological progress in controlled thermonuclear research and the environmental advantages of fusion power. A conceptual drawing of a fusion power reactor located in the center of a populated urban complex appears in figure 32.

The first concept proposed is the use of ultra-high temperature plasmas, in the form of a fusion torch, to reduce *any* material to its basic elements. In the past, energy has been used solely to convert the raw materials of our planet to products useful to man and to power these products to provide the services necessary for an advancing civilization. Most of what man produces becomes a waste and represents a potential pollutant to our air, water and earth. In addition to wastes from the products we have used, a severe pollutant problem arises from our energy sources themselves (gasoline engines; coal, oil, and gas power stations; and, radioactive wastes from fission reactors). It is becoming increasingly difficult to find suitable ways of disposing of wastes without creating some new problem. (Burning trash takes care of a solid waste at the expense of polluting the atmosphere.)

The second law of thermodynamics states that as work is performed entropy increases–that is, the potentiality for the performance of further work declines. Energy, in other words becomes less and less available to do work. This manifests itself in processes such as mining which takes concentrations of ores, fossil fuels, and minerals and diffuses these or the products of their combustion or manufacture over the surface of the earth, the oceans, and in the air.

Coal and oil are taken from the earth and burned, thus reducing them to chemically less available substances like carbon dioxide which are then diffused throughout the atmosphere and the oceans. Iron ore is taken from the mines, manufactured into iron and steel, and eventually diffused in innumerable dumps and fragments of rust over the surface of the earth. Phosphates and potash from mines and from soil are built into foodstuffs, and are finally excreted into the rivers and eventually into the oceans.

To maintain and expand our high-level society, man is rapidly exhausting his geological capital which has been accumulated over hundreds of millions of years in the form of ores and fuels. The use of the fusion torch is not only an alternative to pollution problems, but also has the potential, using energy from controlled nuclear fusion, for a closed–cycle economy which can solve the materials problems of the world by simply circulating a material from one form to another.

Note that although we can conceive a closed-cycle economy in materials, we cannot conceive a closed-cycle economy in energy. To prevent the increase of entropy in the system, auxiliary energy must be imported from outside–i.e., from the sun, from fission, or from fusion.

A second major concept proposed is the use of the fusion torch to transform ultra-high temperature plasma energy into a radiation field. Control of both the frequency and intensity is inherent in the concept. This permits unit process heating to be done *in the body* of a fluid through use of ultraviolet radiation. The present limit on process heating is due to the fact that heat must be transferred from a *surface* to the body of a fluid. This requires pumping of the fluid to remove the heat from the surface by convection and conduction heat transfer processes. The ability to transfer energy from a prime energy source–controlled fusion–to bulk fluids on a large scale opens up many possible applications. Among these are desalination, human and animal waste sterilization, ultraviolet chemistry, energy conversion to electricity through fuel cells, energy storage in portable (pollution free) fuels such as ammonia[89] and as yet unenvisioned applications resulting from recent discoveries such as exciton fission.[90]

Ultra-high temperature plasmas are available *now*, although at a cost in energy. Little thought has gone into their potential use for industrial applications, nor has much imaginative thought gone into taking full advantage of the unique properties of fusion plasmas that will be available in future controlled thermonuclear energy sources. While not attempting to minimize the large amount of research both on fusion itself and on fusion torch physics, it is entertaining to speculate on the vision this concept provides of the future–large cities, operated electrically by clean, safe fusion reactors that eliminate the city's waste products and generate the city's raw materials.

The vision is there, its attainment does not appear to be blocked by nature. Its achievement will depend on the will and the desire of men to see that it is brought about.

ARTISTS CONCEPTION OF FUTURE URBAN FUSION POWER PLANT

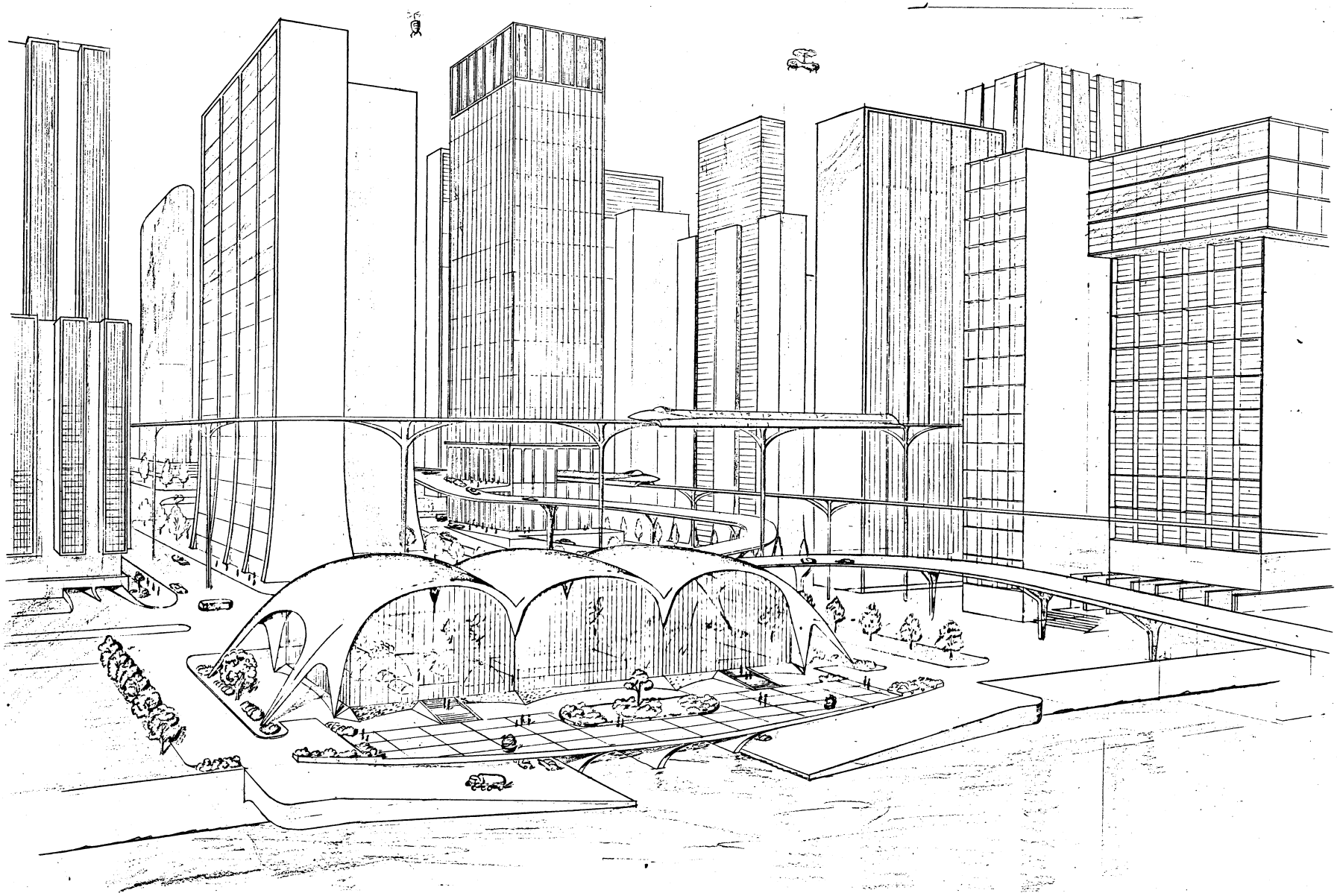


Figure 32

APPENDIX I: ENERGY TRANSPORT TO A SPHERICAL SOLID IMMERSED IN A MAGNETOPLASMA

As indicated in section II, it is important to show that the total energy needed to vaporize a solid with finite dimensions is (a) contained in the plasma and (b) can be transported to the solid in a time small compared to the time needed to transmit the shock wave through the solid. Thermal conductivity is actually anisotropic in a magnetized plasma, being much larger parallel to the magnetic field than perpendicular to it.

The geometry under consideration is shown in figure 33. We assume the solid is spherical, of radius r, and that it is characterized by E_v, the energy needed to vaporize per unit volume, and v_s its shock velocity. The plasma has a density n, and a temperature T.

We can then show that a total energy, E, given by the following equation will be necessary to vaporize the spherical solid:

$$E = \frac{4}{3}\pi r^3 E_v \tag{1}$$

This amount of energy is contained in a cylinder of plasma as shown in the following equation:

$$E = \pi r^2 \cdot 2\ell \left(2 \cdot \frac{3}{2} nkT\right) \tag{2}$$

Solving for ℓ, we find

$$\ell = \frac{2}{9} r \frac{E_v}{nkT} \tag{3}$$

The one dimensional equation for thermal transport in a plasma is:

$$c_v \frac{dT}{dt} = \lambda \frac{d^2T}{dz^2} \tag{4}$$

Dimensional considerations give a diffusion length as follows:

$$\ell^2 = \frac{\lambda}{c_v} t \tag{5}$$

thus $$t = \ell^2 \frac{c_v}{\lambda}$$

or $$t = \frac{\ell^2 \cdot n}{1.47 \times 10^{27}\, T^{5/2}} \tag{6}$$

THERMAL TRANSPORT IN A MAGNETOPLASMA

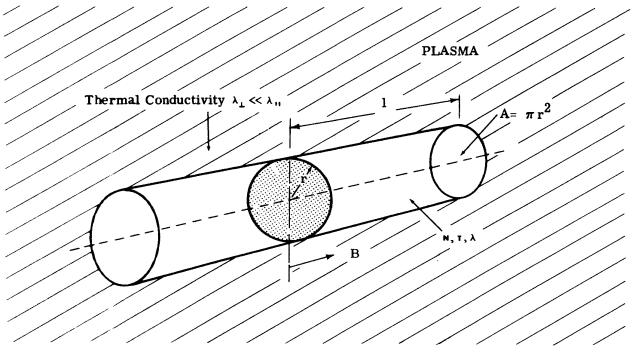


Figure 33

where ℓ is in cm

n is in number/cm^3

and T is in kev

substitution of equation 3 into equation 6 gives us the following expression for the time necessary for the energy required to vaporize a particle to reach it:

$$t = 1.3 \times 10^3 \cdot r^2 \frac{E_v^2}{nT^{9/2}} \tag{7}$$

Thus the condition we are to show is that t should be less than r/v_s, the time required to vaporize.* This condition becomes

$$t = 1.3 \times 10^3 \cdot r^2 \frac{E_v^2}{nT^{9/2}} \leqslant \frac{r}{v_s} \tag{8}$$

*It should be noted that at very low temperatures, λ, in equation 4 must be taken within the spatial derivative and the thermal energy transport is not nearly as rapid as these equations for a *fusion* plasma predict. This is one of the basic reasons for an arc's inability to vaporize solids.

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